Application of Formation Control for Multi-Vehicle Robotic Minesweeping

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Abstract

In an effort to find low cost solutions to Naval minesweeping, a fleet of robot minesweepers equipped with detection sensors and acoustic/magnetic devices is proposed. To ensure maximum sweeping all vehicle movements are coordinated through a supervisor vehicle that determines if vehicles are lost to mine detonation, and re-tasks, as needed, the remaining vehicles to follow tracks left by lost vehicles. A computer program has been developed to evaluate control logic linking supervisor and worker vehicles. The algorithms for track control and vehicle ID reassignment are given and example results shown.

Introduction to the Problem and Concept

The need for robotic minesweeping in very shallow water has led to new concepts for the use of small swimming and crawling vehicles. To be efficient, these vehicles are low cost and would carry mine detonation devices such as magnetic and explosive systems that could neutralize any mine found in their path. Vehicles are destroyed in the process, but the field will be cleared. At issue is the command and control of such a multi-vehicle system. Clearly, they carry a navigational suite for control to a desired track. They also carry a mine detection system, which has a limited range, and the magnetic influence sweeper has limited range. There is an initial track spacing less than the range of the magnetic sweeper such that some degree of overlap of vehicle coverage is obtained. However, when a detonation occurs, not only would the vehicle be lost, but also, other vehicles within a radius of influence would also be lost.

The system control requires that spacing between vehicles be maximized at all times so as to limit collateral damage between vehicles. Also, when one vehicle is lost to a mine, its remaining sweep path is left unswept causing what is known as a 'holiday' in coverage. Unless other remaining vehicles adapt their paths to provide systematic coverage of swept area, the concept would leave mines undetonated.

In this paper we explore the use of swimmer vehicles to perform mine detonation with a supervisory vehicle that re-directs the paths of remaining vehicles to cover these holidays and produce high levels of overall clearance.

Concept of Overlap

Optimal search patterns for mine fields of unknown characteristics have been the study of many. Koopman and Stone discuss various methods. When the field is rectangular, a linear sweep giving uniform and complete area coverage produces the result that clearance is proportional to time with a probability of clearance depending on the sensor used. With sensors that have less than a unity probability of detection, multiple area overlapping is used so that if p is the sensors probability of detect with m passes, the overall probability becomes .

$$P_{overall} = [1 - (1 - p)^m]$$

So, to increase P, and to overcome navigational errors, sweeping overlap is used as shown in Figure 1. The vehicle paths over the area are determined from a spacing giving this overlap. The paths to be followed are defined in terms of global way points (GWPs) which define tracks for each vehicle to follow.

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14. ABSTRACT
In an effort to find low cost solutions to Naval minesweeping, a fleet of robot minesweepers equipped with detection sensors and acoustic/magnetic devices is proposed. To ensure maximum sweeping all vehicle movements are coordinated through a supervisor vehicle that determines if vehicles are lost to mine detonation, and re-tasks, as needed, the remaining vehicles to follow tracks left by lost vehicles. A computer program has been developed to evaluate control logic linking supervisor and worker vehicles. The algorithms for track control and vehicle ID reassignment are given and example results shown.

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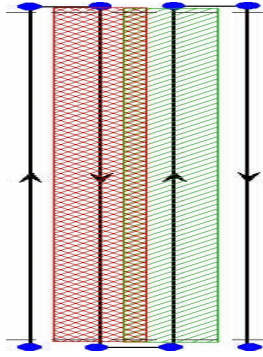Prescribed by ANSI Std Z39-18

Figure 1 Illustration of Sweeping Overlap Between Tracks

With no losses, each vehicle performs track following behaviors, navigating to minimize cross track errors at a specified depth or altitude above bottom (Marco, Healey,2000).

With multiple vehicles, each follows a predetermined track separated in space and time so as to increase the separation distance between vehicles. This separation is necessary in case of one detonated mine causing damage to more than one vehicle. Such an initial deployment is shown in Figure 2.
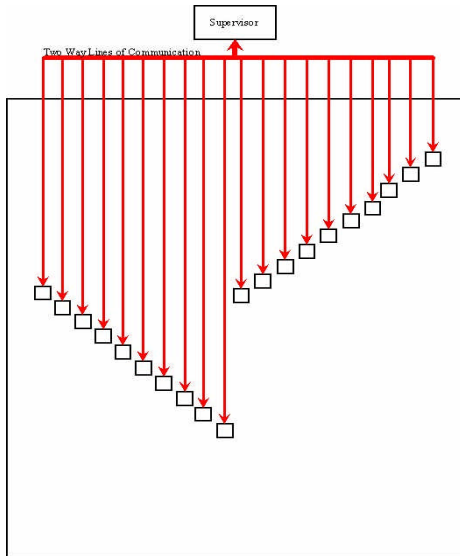

Figure 2 Initial spacing of vehicles

Vehicle Control, ID and Supervisory Track Redirect

In order to support the concept of vehicle re-tasking when one is lost, the vehicles utilize a dual identification scheme. Each vehicle is assigned a primary, permanent ID as well as a secondary, changeable ID number, which is based on the number of vehicles remaining in the scenario. The vehicle is tracked and all vehicle data is recorded using its permanent name. For computational purposes and data management internal to the system, the permanent ID of the first vehicle in line is assigned a value of zero and the last vehicle assigned a value of one minus the total number of vehicles. However, in order to try to reduce the confusion that this practice might present when viewing graphical displays of the data, the permanent vehicle ID correlates directly to its position in line. For example, the first vehicle in line is referred to as vehicle one and the twentieth vehicle in line is vehicle twenty. Initially, both the primary ID and secondary ID are identical. However, as vehicles are killed, the secondary ID for all vehicles possessing a primary ID greater than that of the killed vehicle will be reduced by one. This then allows the vehicles tracks to be re-allocated in a fairly simple manner. This concept can best be summarized by the following variable re-assignment logic.

Initially
$$vehicle\_id\ (i) = i; \qquad i = 0, N - 1$$

If k^{th} vehicle is killed
$$vehicle\_id\ (i) = i; \qquad i = 0, k - 1$$
$$vehicle\_id\ (i) = i - 1; \qquad i = k + 1, n - 1$$
$$vehicle\_id\ (i) = dead; \qquad i = k$$
where
$$N = \#\ of\ initial\ vehicles$$
$$n = \#\ of\ remaining\ vehicles\ at\ any\ given\ time$$

Track Re-Allocation
Basis of Re-allocation

When the supervisor determines a track re-allocation is necessary, the magnitude of the shift must be calculated and tracks to the new GWPs must be determined and disseminated to the swimming vehicles. As an example, Figure 3 clearly shows such a shift.
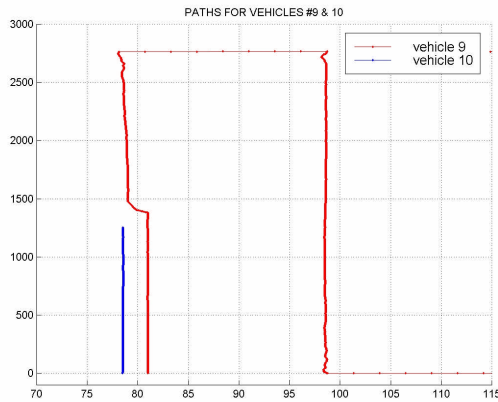
Figure 3 Track Shift After Loss of a Vehicle

As seen in this example, vehicle 10 was clearly lost to a mine in an area that correlates to the first mine danger area. When this occurred, vehicle 9, as directed by the supervisor, obviously alters course in order to shift its track to head for the newly assigned GWP that was previously allocated to vehicle 10. This allows the vehicles to search and sweep the maximum amount of area possible, leaving only minimal gaps of un-covered area (holidays) in the process. Other vehicles with ID numbers less than nine follow suit, but were left out of the figure for clarity.

Logically, determination of the course change required for the track re-allocation is a function of the vehicle's position. The vehicles position is calculated as a horizontal offset (DX) from the position of the first vehicle, which is considered to be a reference point for the other vehicles.

Calculation of and usage of DX

The idea of vehicle ID re-assignment is the critical factor in determining a vehicle's desired horizontal offset. The other critical assumption is that the vehicles are on track and have not deviated beyond the limits of navigational error. In reality, this may be a problem due to varying factors such as ocean current forces, vehicle drag forces, and navigational system reliability, however, for the purposes of this research, these factors were ignored. So, under this assumption, simply knowing that the spacing between vehicles is to remain constant, coupled with the concept of vehicle ID reassignment, the current delta of the vehicle is given by

$$DX\,(i) = \text{vehicle id}\,(i) \times \text{vehicle spacing}.$$

Once DX is calculated, the supervisor enters the data into a series of conditional loops. Inside of these loops, DX is compared with the position of the desired GWP. The final result being the updated track, as seen in Figure 3, that takes the swimmer vehicle to the point where it can resume its nearly vertical path to its newly assigned GWP. Upon reaching the GWP, the swimmer using its updated GWP file continues with its regular search pattern until the operation ends or another mine is sensed.

Supervisor / Swimmer Control Logic

Fundamental to understanding the complex nature on which this concept is built is to comprehend the logic of its basis. Figure 4 displays this logic in an easy to follow graphical format (Ludwig, 2000). This logic diagram is best considered as three diagrams built into one. The first of these three diagrams being a simple two block diagram linking the swimmer with the supervisor. Each of the vehicles is represented by one of the two large outer boxes of the diagram. The large double-sided arrow connecting the communications port of each represents the two-way communications link between the vehicles
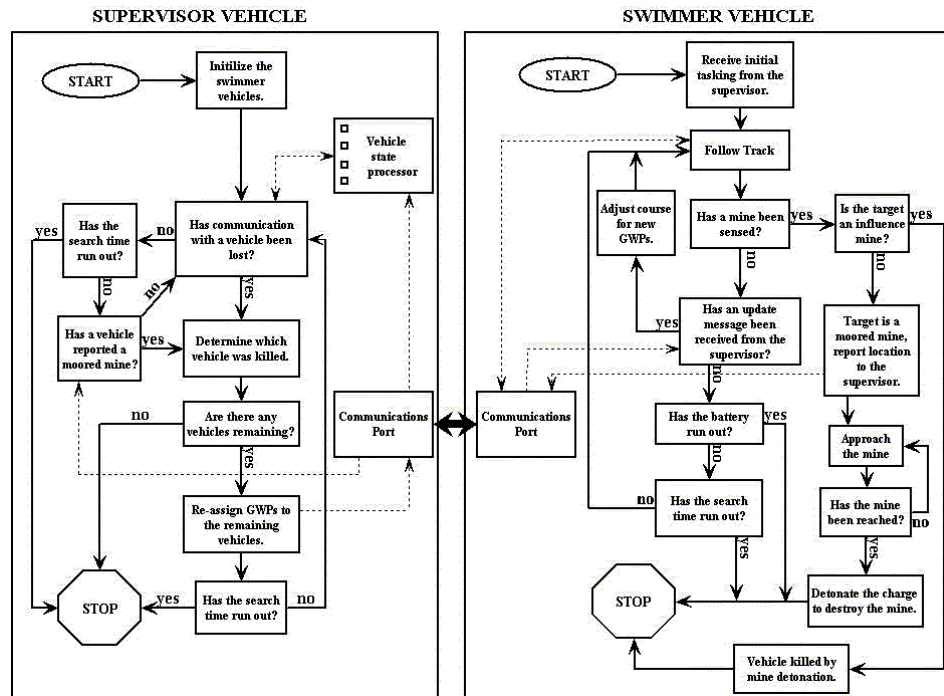
Figure 4 System Control Logic

The second and third logic diagrams are contained within each vehicle block, and represent diagrams specific to that vehicles operations. Dashed lines represent all internal communications and the solid lines represent all logic flow. In a broader view of the scenario, the third diagram would be repeated for as many swimmer vehicles as were utilized for that operation, and the supervisor vehicle would receive input through its communications port from all of the swimmer vehicles, as reflected in Figure 4.

The second diagram, that of the supervisor vehicle, shows the vehicle state processor and its link to the decision process within the supervisor. As communication is lost with a vehicle, the supervisor determines which vehicle was killed, determines if any vehicles are remaining, if so, re-assigns tracks based on GWPs. The process is repeated until the search time runs out or there are no more vehicles remaining. Loss of communications with a vehicle is initiated either by the loss of a signal from a vehicle or by a report of a vehicle locating and starting the demolition process of a moored mine. Additionally, it is envisioned that the vehicle state processor could as necessary

initiate a query process of all vehicles to determine their status.

The third diagram shows the swimmer vehicle logic assuming it is following its assigned track and sending a signal to the supervisor showing that it remains alive until either sensing a mine or receiving an updated track. For the purposes of the flow chart, the term sensed is used to distinguish between the vehicle detecting a moored mine or an influence mine detecting the swimmer. Once the vehicle senses a mine, the chart shows a logic step of determining whether the mine is an influence mine or not. This is a step to demonstrate the distinction between the mine types used in the scenario. In reality the mine would determine this for the vehicle by detonating and destroying the vehicle if it were an influence mine. If the sensed mine is a moored mine, the report reflecting this is shown going out to the supervisor. The diagram also illustrates the vehicle's decision to change its track once it receives an update message from the supervisor. The vehicle continually repeats the process until it is killed, its battery runs out, or the search time is expired.

Parameter	Setting	Default Value	Modeling Method
Sensor Width	User Input	-	Input Statement
Vehicle Spacing	User Input	½ Sensor Width	Input Statement
Turn Time	1 sec	-	Fixed
Navigational Error	0 – 2 m	-	Random Number
Mine Placement Position Error	0 – 1 m	-	Random Number
Influence Mine "Shock Factor"	25 m radius	-	Fixed
Moored Mine "Shock Factor"	10 m radius	-	Fixed
Delay Time to Destroy Moored Mines	15 Sec	-	Fixed
Vehicle Delay Time	Function	-	Calculated
Vehicle Speed	User Input	-	Input Statement
Overlap	Function	100%	Calculated
Number of Vehicles	User Input	-	Input Argument
Number of Iterations	User Input	-	Input Argument
Length of Simulation	User Input	21600 sec	Input Statement

Table 1 Program Parameter Setting

Results

A computer simulation program has been developed to simulate the supervisor-multi-vehicle system behavior. The details of results and the study of effects of different parameter settings are all given in (Ludwig, 2000). The parameters of a particular result are given in Table 1 above. The path response for each of 20 vehicles is shown in Figure 5. As vehicles sweep along their initially planned tracks, one will occasionally be blown up. The supervisor recognizes that the vehicle is now lost and reassigns the secondary ID of the next nearest vehicle to assume the track of the lost one. Thus a continual shifting of the vehicle path s and tracks occurs until the whole field is swept.

Conclusion

The problem of robotic minesweeping is extremely complex, and must allow for multiple scenarios. Accordingly, due to the preliminary nature of this research, its scope was limited to verification of the validity of the concept.   This was accomplished through detailed analysis of simulation code, improving the code, and conducting simulations to verify the results.
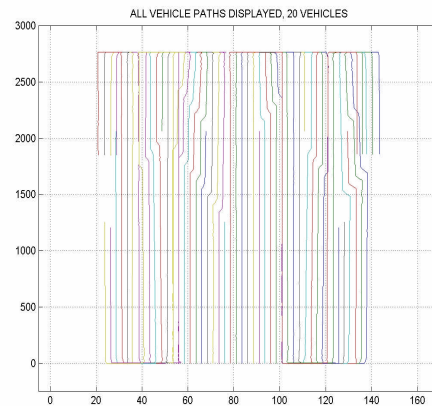

Figure 5 A 20 Vehicle System In A Minesweeping Operation. One Vehicle Is Detonated And Another Moves Over To Take Its Place.

During the process of analyzing the code, four topics were identified as primary areas of concentration. These included the principle of overlap, effects of varying the turn time, vehicle identification procedures, and track re-allocation. Of these four areas, one, the effects of turn time, was found to be not as critical as previously thought.

Specific improvements to the code were made in the areas concerning calculation of

overlap and track re-allocation. Additionally, minor changes were made throughout the code to help make it a more useful tool.

Simulations were conducted to verify the concept. While not the specific goal of the simulations, ballpark figures for the optimization of sensor width and vehicle spacing were uncovered. Additionally, without taking into consideration any of the resistive forces, certain limitations of using slower speed vehicles for the operations were shown.

Overall, this study provided extremely encouraging results and validated the concept of multi-vehicle fleets of robotic swimming vehicles being used for minesweeping operations. Certainly as the myriad of technologies supporting this concept grows, so do the possibilities.

Acknowledgements

References

Koopman, Bernard O., *Search and Screening: general principles with historical applications*, Pergamon Press, 1980.

Stone, J. A., *Theory of Optimal Search*, Academic Press, 1975.

Ludwig, P, *"Formation Control for Multi-Vehicle Robotic Minesweeping"* MSME Thesis, Naval Postgraduate School, Monterey, CA. June 2000

Marco, D.B., Healey, A.J., *Current Developments in Underwater Vehicle Control and Navigation: The NPS ARIES AUV* , Proceedings IEEE Oceans 2000, September 11-14, Providence, RI, September 2000 ISBN#0-7803-6554-2